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Clay Grouting Mechanisms and Applications

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Abstract

Grouting in clay soils could easily lead to a poor grouting efficiency because of a lack of good understanding of the fundamental clay grouting mechanisms and grout rheological characteristics and grout hose system. Additionally, for the purpose of lifting tilted building and/or structure in clay soils, the dissipation of the excess porewater pressure generated during grout injection is likely to lead a negative final compensation efficiency. To address the said key engineering issues, a comprehensive study on the properties of grouts and effective grout injection is deemed to be necessary for the success of the project. Since grouting in clay soils rules out any other ground improvement methods other than fracturing grouting, the chapter presented herein would introduce not only previous studies for a better understanding of the grout properties but also two case histories for demonstrating how the final compensation efficiency can be improved by introducing the proposed simultaneous and multiple grouting technique.

Keywords: soft clay, fracturing grouting, ground improvement, compensation efficiency, rheological characteristics

1. Introduction

Foundation soil bearing capacity for Taipei basin is usually inadequate, where a 40–55-m-thick alluvial formation (the Sungshan formation) of alternating soft clay and silty sand layers is deposited, followed by a gravel formation (the Chingmei gravel formation) [1, 2]. The shear strength of the soft soil deposits due to the water contents close to their liquid limits is very low, leading to an inability of supporting upper buildings and/or structures [3–7]. To tackle this key engineering issue, grouting technologies have been widely adopted to improve the mechanical properties of the soft soil deposits [8–23]. Notwithstanding that, the effectiveness of grouting in such geological conditions can be significantly affected by the configuration of

grouting programme. The differential settlement or tilting of building, for instance, can be contributed not only by the soil right below the building foundation but by the successive soils. Thus, a grouting programme aimed to first stabilise the successive soils by 'stabilisation' grouting and then to lift the tilted building by 'jacking-up' grouting in the foundation soil is proved to be effective [24]. In the event that the grouting programme is designed to improve the properties of the foundation soil only, the jacking of the tilted building would not be effectively implemented due to a lack of the sufficient reaction forces given by the successive soils. Additionally, the intrusion of grouts may swell the cohesive soil and generate the positive excess porewater pressure. As long as the porewater pressure dissipates along with time, the associated settlement could override the heave generated during grout intrusion and thus result in a negative final compensation efficiency which is defined as a ratio of the total heaved volume to the injected volume of grouts [25–29]. Since the fracturing grouting due to easy travelling of the low viscosity grouts could generate higher porewater pressure than compaction grouting, regrouting at the same injection point is deemed to be necessary in order to change the stress state of cohesive soil to the overconsolidated state from its ordinary state [24, 30]. Any further grouting activity would only generate negative excess porewater pressure, and resettlement would not be occurred, thereby improving the final compensation efficiency. If both closer spacing between grout injection points and simultaneous injection are introduced, the final compensation efficiency can be further improved [27]. The above indicates that configuration and design parameters of the grouting programme play a leading role in the success of project.

The objectives of this study are (i) to present the results of an application of this proposed simultaneous and multiple grouting technique for levelling two tilted buildings seated on soft soil deposits in Taipei basin, (ii) to verify the effectiveness of introducing a grouting programme consisting of the stabilisation grouting of first stage and jacking-up grouting of the second stage by analysing the elevated and settled efficiencies and (iii) to outline the lessons learnt from the case studies.

2. Grouting mechanisms

Hydrofracturing of soil occurs in many important geotechnical engineering issues. It corresponds to the process of initiation and propagation of a crack by injecting water and air as well as chemicals into soils. As the pressure of the fluid injected surpasses a certain threshold value, the hydrofracturing of soil is thus triggered. A typical application of hydrofracturing is fracturing grouting. The fracturing grouting that involves the intentional hydrofracturing of soil with a low viscosity grout to generate a network of interconnected grout lenses has been extensively used to create surface heave and compensate settlements as well as strengthen the soil. To implement an effective field application of the fracturing grouting, a good understanding of its fundamental mechanism is deemed to be necessary. Wong Ron and Alfaro Marolo carried out a field mapping of sand-propped hydraulic fractures at a contamination remedial site where the ground is primarily consisted of silt and clay. The fractures

were found to be nearly horizontal, indicating that the ground is overconsolidated, with a K_0 value greater than unity [31]. The sand proppant was thicker at locations where soils were relatively weak, but there was no strong evidence that soil stratigraphy at this worksite controlled the orientation of the fractures. Murdoch and Slack reported similar results in sand-propped hydraulic fractures [32]. Additionally, the horizontal fractures imply that the shallow soil strata should be overconsolidated. Moreover, the elevated volume would be considerably smaller than the injected volume in the event the hydraulic fractures vented to the ground surface. Liu and Yuan established an in situ slurry fracturing apparatus to analyse the slurry fracturing and fracture propagation phenomena [33]. It was observed that the fracturing pressure was highly related to the soil and slurry properties and that slurry with large bulk density and high viscosity was beneficial in preventing slurry fracture propagation. Conducting grouting in clay due to its low permeability rules out any other grouting techniques other than fracturing grouting. The excess porewater pressure generated during grout injection is greater than the in situ effective stress, leading to fractures in the surrounding clay. Existence of fractures accelerates the consolidation process and shortens the strength increase time due to consolidation. During injection, the fractures provide a channel for exchangeable cations, which make the strength increase due to chemical reactions much more quickly than anticipated. Additionally, the compensation efficiency may not be governed by clay type but by the setting time of grout, soil stress history, injection volume of grout and so on. However, the high mobility and low viscosity of the grout can lead to an inability of limiting the travel of grout, thereby resulting in a lower soil-heaved volume to injected volume of grout ratio also known as the grouting efficiency. The grouting efficiency is generally smaller than 1 due to the loss of fluid, resulting from the bleeding effect of grout and escape of the grout from the designated area by migration along fractures, and the ground settlement caused by the dissipation of excess porewater pressure generated in injection [31]. Marchi et al. carried out a comprehensive case study in Venice where a rather unique soil fracturing intervention was implemented to improve the mechanical properties of the soft silty clay underlying the ancient Frari bell tower [34]. For soils with negative values of liquidity index, the gradients from the plots of fracturing pressure against initial confining pressure are approximately 2, which indicated the fracture initiated by tensile failure in these cases, while for soils with positive values of liquidity index, the gradients are approximately 1, indicating that the fracture was triggered by shear failure. Komiya et al. conducted a field trial of shield tunnelling in a deep soft clay deposit to investigate the long-term consolidation effect on grouting efficiency [25]. The grouting programme was consisted of the tail void grouting and grout jacking. In both cases, the monitoring results indicate that the upward displacement owing to grout injection was negated by the consolidation settlement resulting in a net settlement. The considerable consolidation of clay after grout injection due to the dissipation of the excess porewater pressure generated as the grout intruded the sensitive and compressible clay contributed to this phenomenon. This also indicates that the grouting efficiency in soft clay may be negative.

It is reported by Au et al. that for normally consolidated or slightly overconsolidated clays, the significant decrease in the grouting efficiency with time was due to the dissipation of

the positive excess porewater pressure generated during grout injection [26]. However, for heavily overconsolidated clays, the excess porewater pressure was positive at the injection boundary, but it was negative at the outer boundary due to dilative behaviour of the clay. The compression around the injection point induced by the dissipation of the positive excess porewater pressure and swelling some distance away from the injection point caused by the dissipation of the negative excess porewater pressure led to a negligible consolidation effect. As discussed, the bleeding effect of grout has been deemed to be one of the factors affecting the grouting efficiency. Au et al. conducted additional injection tests with grouts that were prepared with the water-to-cement (w/c) ratios of 0.5, 1 and 3, respectively, using the 50-mm diameter oedometer [26]. The final grouting efficiency was reduced from about 20% for the grout with the w/c ratio of 0.5 to around -30% for the grout with the w/c ratio of 3. The higher the solid content of grout, the lesser the bleeding effect of grout, and the higher the final grouting efficiency. The effect of boundary condition was also examined by injecting 5 ml of grout into the modified oedometers with the diameters of 50 mm and 100 mm, respectively [26]. The results show that the reduction in the radial boundary size enabled the final grouting efficiency to be improved dramatically as the overconsolidation ratio was within a range of 1–2. In other words, the smaller the spacing of injection point, the smaller the magnitude and extent of excess porewater pressure, and the higher the final grouting efficiency. It is common practice to introduce the tube-a-manchette (TAM) while performing compensation grouting, which allows grout to be injected many times from the same injection port. In the case that a given volume of grout is injected over a fixed area, it is possible to either regROUT many times at the same port with smaller injection volumes or, conversely, conduct a small number of regROUTing but with larger injection volumes. A series of injection tests comprising the regROUTing injection and single injection tests were undertaken in normally consolidated clay specimens to investigate the effect of waiting period on the long-term grouting efficiency after injection [26]. An injection of 5 ml for each injection was made four times for the regROUTing injection tests. The test results were compared with the result of a single injection test which was undertaken by injecting 20 ml at once. The results show that in the stage of consolidation, more excess porewater pressure was generated in the subsequent injections for the regROUTing injection test, thereby leading to a lower grouting efficiency than that from the single injection test. Additionally, the efficiency of compensation grouting defined as the ratio of building settled volume to total injected volume of grout may be further reduced as only the grout beneath the mat foundation can contribute to the effective lift of tilted building. Moreover, injection of extra quick setting grout can only be achieved by introducing the two-shot grout hose system [35]. The shorter the grout gel time, the lesser the excess porewater pressure generated, and the higher the final compensation efficiency. To summarise, it is evident that there are many factors (soil stress state, boundary condition, bleeding of grout, regROUTing, grout rheological characteristics, grout hose system and so on) affecting the final compensation efficiency. Lifting tilted building in soft clay deposit can be better achieved by introducing a grouting programme that at least takes the previously discussed factors into account. Also, the two-stage grouting consisting of the stabilisation grouting of first-stage and jacking-up grouting of second stage may be used to ensuring the final compensation efficiency.

3. Case descriptions

3.1. Engineering geology

Based upon the preliminary geological investigation [36], the ground for Case A is generally consisted of a 1.5-m-thick surface backfill, a 4.5-m-thick low plasticity clay, a 4-m-thick silty sand and a successive very soft silty clay, as shown in **Figure 1**. The blow count N value for the clays varies from 1 to 4, whereas for the sands it varies from 5 to 10. The groundwater level is close to the ground surface. The soft soil deposits can thus easily get softened once disturbed or even washed away as subjected to significant hydraulic gradients.

The geological profile at the worksite of Case B is consisted of a 4-m-thick alluvial loam, a 7-m-thick very soft silty clay and an underlying soft silty clay, as shown in **Figure 2**. The static groundwater level in the vicinity of the worksite is some 2 m below the surface. The N value varies from 1 to 2 for the very soft silty clay, whereas for the soft silty clay, it varies from 2 to 3. The soft clays thus can behave as a fluid once subjected to construction disturbances.

3.2. Grouting programme

In the Case A, the eight-storey reinforced concrete building with one-storey basement was seated on the silty sand. The nonuniform consolidation of the successive silty clay led to the tilting of the eight-storey building afterwards. Since the tilting of the eight-storey building was amplified along with time, jacking the tilted eight-storey building back to the acceptable range of tilting was urgently needed. After considering all the possible alternatives to level up the tilted eight-storey building, grouting method was chosen due to the two reasons, that

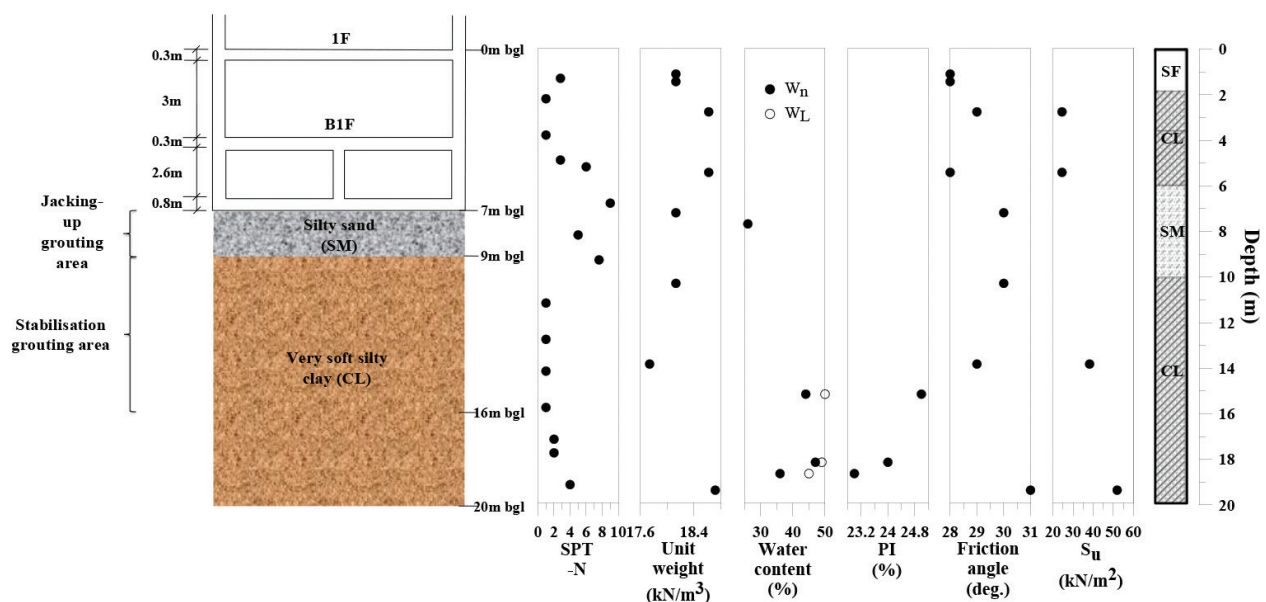


Figure 1. Geological profile of worksite and properties of soft soil deposits (Case A).

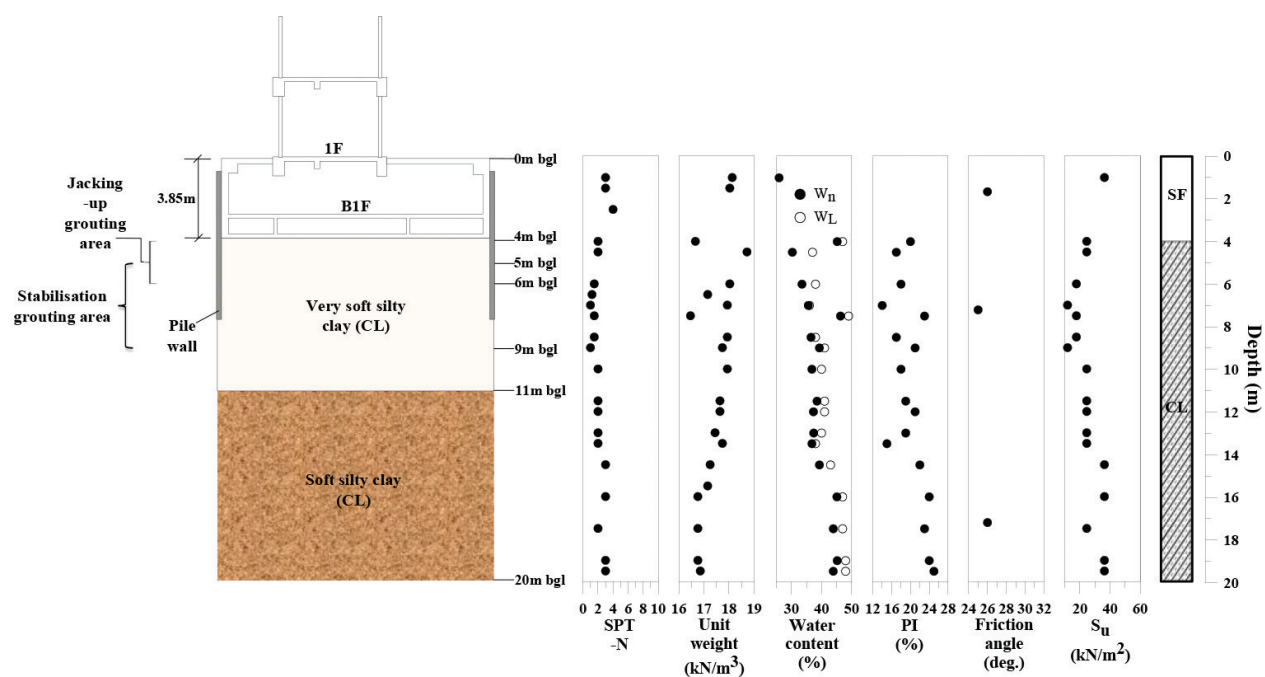


Figure 2. Geological profile of worksite and properties of soft soil deposits (Case B).

is, (1) the concentrated grouting pressure during injection was distributed over the rigid mat foundation and would not damage the integrity of the tilted building, and (2) the unoccupied basement provided free and easy access to install grouting pipes and associated grout injection facilities. A reaction block right below the foundation soil should be given prior to the implementation of the jacking-up grouting. In this regard, the first stage of sleeve grouting (the stabilisation grouting) with the mild setting grout was carried out at a depth range of 9–16 m below the ground surface using a series of sleeve pipes (known as TAM). The pipe spacing varied from 3 to 4 m, and the layout of the 35 sleeve pipes is shown in Figure 3. The grout began intruding the soils upwards from the bottom of each sleeve pipe through one rubber sleeve at a period of time for a total of 15 rubber sleeves. As the building tilted to the southwest, the grout intake per sleeve pipe for the three different grouted zones depicted in red, black and green in Figure 3 was 16.8, 14.7 and 6.3 m³, respectively, and was distributed evenly to 14 ports for 8 cycles of injection. The grout mix adopted in this stage is shown in Table 1.

Once the successive silty clay was strong enough to serve as a reaction block, the second stage of JOG grouting (the jacking-up grouting) was carried out where the quick setting grout was injected into the silty sand right below the mat foundation at a depth range of 7–9 m below the surface to level the tilted building. Each JOG grouting pipe was 20 cm offset from the sleeve pipe installed previously. To achieve the purpose of simultaneous injection, a multiple injection system involved with 18 JOG grouting pipes and a central controlling unit were introduced in grouting operations, as shown in Figure 4. The daily monitoring records from SB 1 to SB 7 were used for determining the grouting duration at each JOG grouting pipe and grouting order of each injection cycle. The injection of the extremely short setting grouts (Table 2) was achieved using the double tube, thereby preventing premature solidification and limiting the travel of grouts. Two types of grouts separately injected were mixed and solidified at the outlet of the

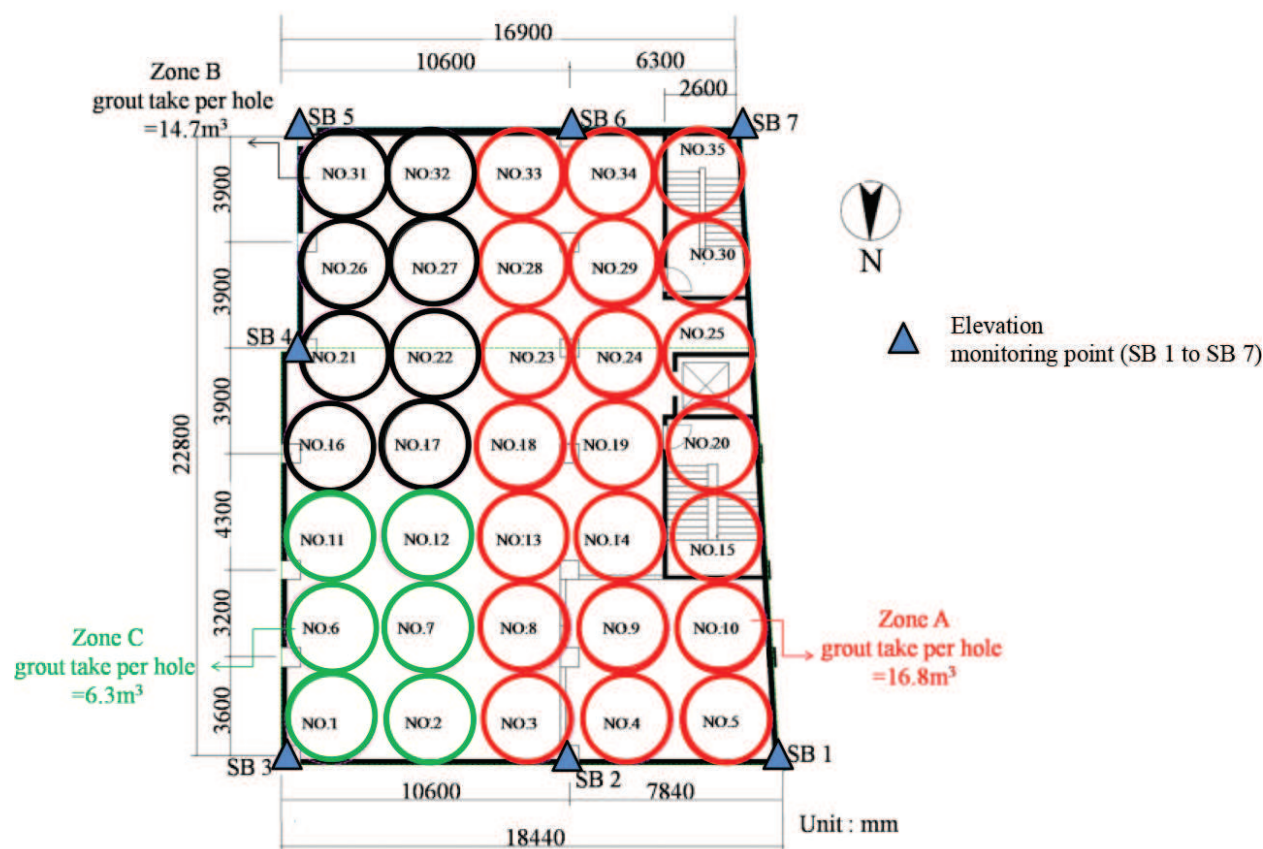


Figure 3. Layout of 35 sleeve pipes (Case A).

double tube. Thus, the grouting mode (penetration or fracturing) could be chosen by varying the cycle time which is defined by the summation of injection time for each grouting pipe in the simultaneous injection operations. The grout due to the cycle time shorter than the setting time would penetrate through the yet-to-be hardened zone from previous injection to create a reaction block. In the event that the cycle time is longer than the setting time, the grout was injected repeatedly into the region where the grout from previous injection had already been hardened to level tilted building. With this simultaneous injection system, the travel of grouts was effectively limited, and the heave of ground was successfully initiated, jacking up the tilted building. Since performing injection in clay easily promotes hydrofracturing of soil due to its low permeability. During grouting works at the Case B, the soft clay deposits right below the mat foundation of this eight-storey building, thus ruled out any other ground improvement methods other than fracturing grouting. Because the final compensation efficiency could

	Cement	Calcium oxide	Water
Weight (kg)	400	20	866
Volume (L)	1000		

Table 1. Grout mixture for the stabilisation grouting (Case A).

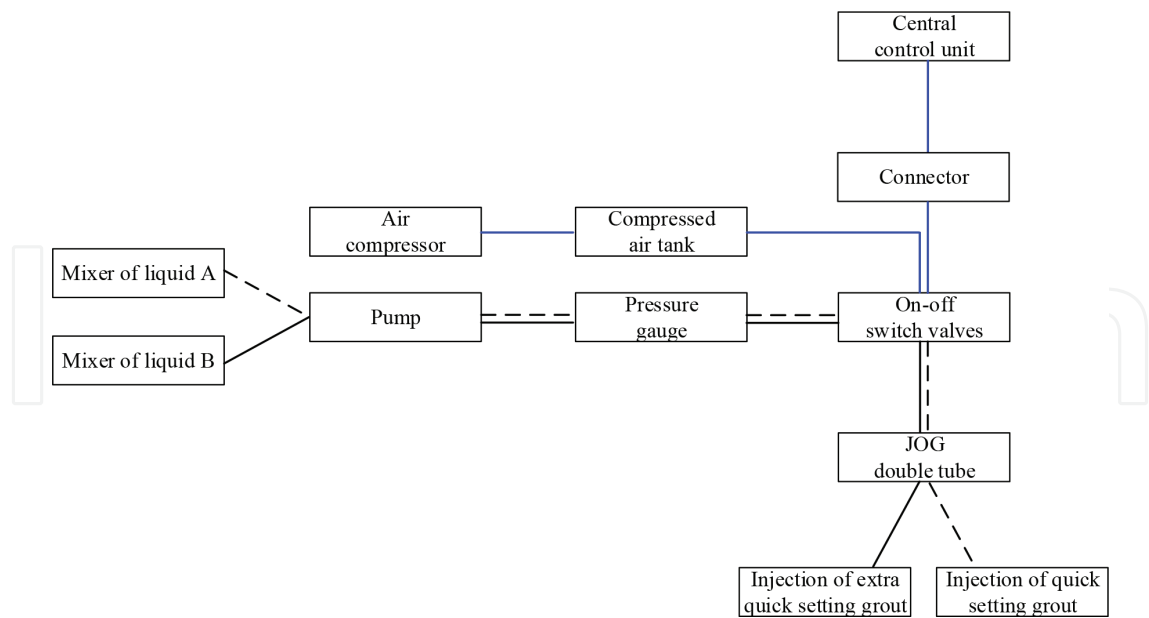


Figure 4. Illustration of the proposed multiple and simultaneous grouting system.

A liquid (200 L)				
	PR silica	SG hardener	Water	
Volume (L)	56.7	11	132.3	
B liquid (200 L)				
	Cement	Permarock	PR actor	Water
Weight (kg)	100 ± 25	12.5 ± 2.5	5 ± 2	160

Table 2. Grout mixture with 2-s setting time for the jacking-up grouting (Case A).

A liquid (500 L)				
	Cement	Pulverised coal	CaO	Water
Weight (kg)	400	300	90	250
B liquid (500 L)				
	Na ₂ O-3SiO ₂		Water	
Volume (L)	150		350	

Table 3. Grout mixture with 25-s setting time for the stabilisation grouting (Case B).

be largely improved with the repetitive injection procedure, a total of 49 sleeve pipes were installed 5 m beyond the mat foundation. Their locations are depicted by solid grey circle in **Figures 7a** and **8a**. The spacing between the sleeve pipes was 2 m. The grout hose system of 1.5 shot with a quick setting grout (**Table 3**) was introduced to ensuring the compensation efficiency. Similarly, two stages of grouting were implemented; the first stage of sleeve

A liquid (500 L)				
	Cement	Pulverised coal	CaO	Water
Weight (kg)	400	300	90	325
B liquid (500 L)				
	Na ₂ O-3SiO ₂	Water		
Volume (L)	250	250		

Table 4. Grout mixture with 20-s setting time for the jacking-up grouting (Case B).

grouting (the stabilisation grouting) with a maximum grouting pressure of 20 kg/cm² was to stabilise the soft clays in the depth range of 5–9 m to provide the reaction required in the next jacking-up stage, and the second stage of sleeve grouting (the jacking-up grouting) was to intrude the clays ranging from 4 to 6 m depth to level up the tilted building. The grout mixture used in the jacking-up grouting is shown in **Table 4**.

4. Analysis and discussions

4.1. Multiple and simultaneous grouting results

The effectiveness of the proposed multiple and simultaneous grouting programme for the Case A was demonstrated using the measured column elevations from SB 1 to SB 7. The column elevation before each day grouting and the change in the column elevation after grouting were measured. **Figure 5** shows the relationship between the grout take and the change in the column elevation for this simultaneous and multiple jacking-up grouting. Most of grouts were injected into the southwest corner (SB 7), and the associated change in the column elevation measured 15.6 cm at the end of the grouting, as shown in **Figure 5**. Only a few grouts were injected into the northeast corner (SB3) and resulted in a nearly unchanged column elevation. The elevation change contour lines of the mat foundation were also prepared based upon the monitoring results of the column elevation change. The volume between the mat foundation contour lines before grouting and those after grouting represented the elevated volume of tilted building at the end of each day. Additionally, the volume between the mat foundation contour lines after grouting and those before next day grouting corresponded to the overnight settled volume of tilted building caused by the dissipation of excess porewater pressure resulting from previous grouting. Thus, both the elevated efficiencies defined by the ratio of the elevated volume to the injected grout volume and the settled efficiency defined by the ratio of the settled volume to the injected grout volume can be derived.

Figure 6 shows the cumulative elevated, settled and injected grout volumes, respectively, against each grouting day of this jacking-up grouting. From day one, the elevated volumes were greater than the settled volumes for each grouting day, which indicated a benefit from the reaction block, resulting from the stabilisation grouting. In the event that the soils subjected to the stabilisation grouting are not satisfactorily strengthened and showed an inability of

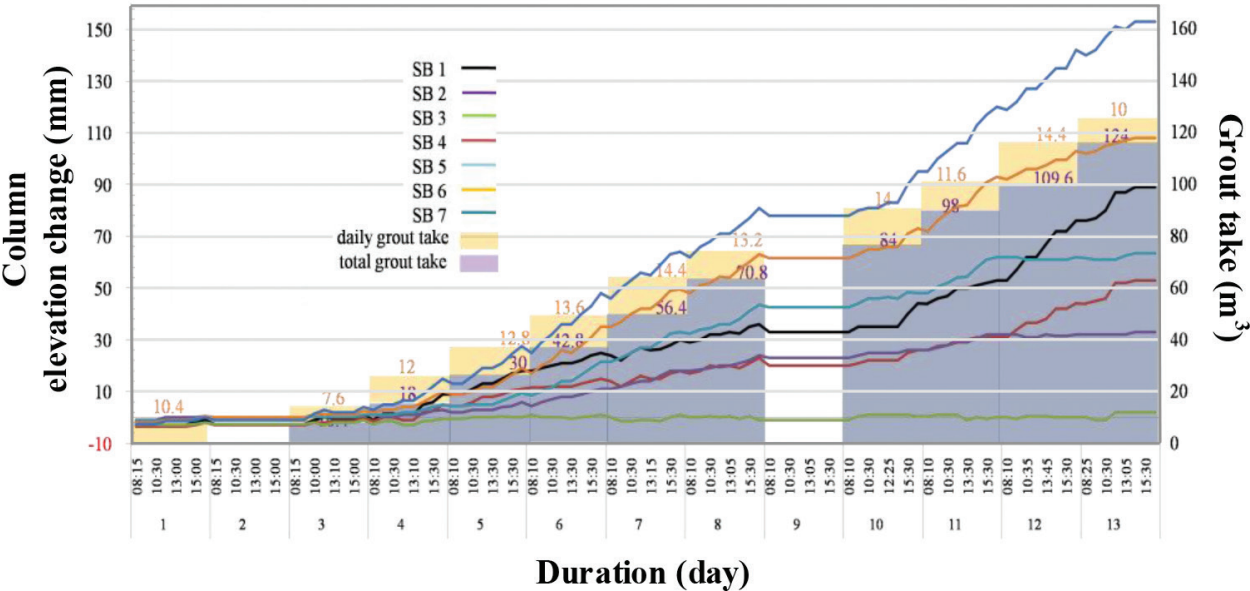


Figure 5. Relationship between the column elevation change and the grout take for the jacking-up grouting (Case A).

providing sufficient reaction force for levelling the tilted building, the final compensation efficiency may be negative as the resettlement overrides the ground heave. The results from the end of the jacking-up grouting showed that the elevated, settled and injected grout volumes measured 35.7, 3.9 and 134 m³, respectively, corresponding to the final compensation efficiency of 23.7% which is derived by subtracting the settled efficiency of 2.9% from the elevated efficiency of 26.6%. Upon the completion of the jacking-up grouting, this building initially tilted to the southwest at an angle of 1/68 was restored to the near level at an angle of 1/328 in 11 days.

Figure 7 shows the elevated, settled and injected grout volumes, respectively, from day one of the jacking-up grouting for the Case B. The injected grout volume measured 8.7 m³,

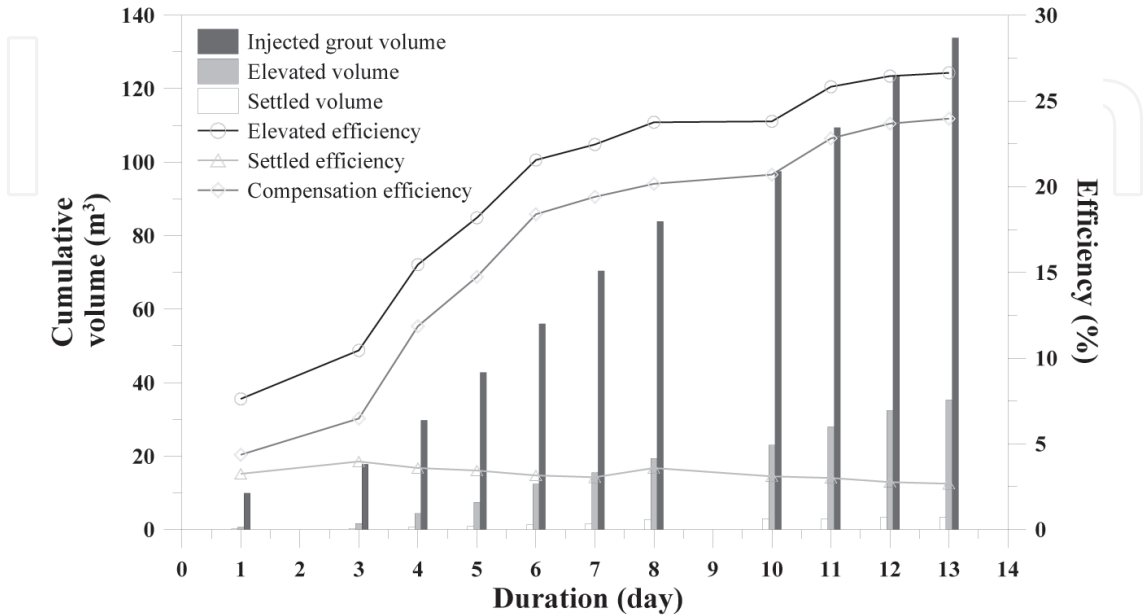


Figure 6. Variations of the elevated, settled and compensation efficiencies for the jacking-up grouting (Case A).

while the elevated volume measured 3.2 m^3 , corresponding to the migrated volume being equal to 5.5 m^3 . The overnight settled volume measured 3.9 m^3 however was greater than the elevated volume of 3.2 m^3 , which indicated the compensation efficiency being negative.

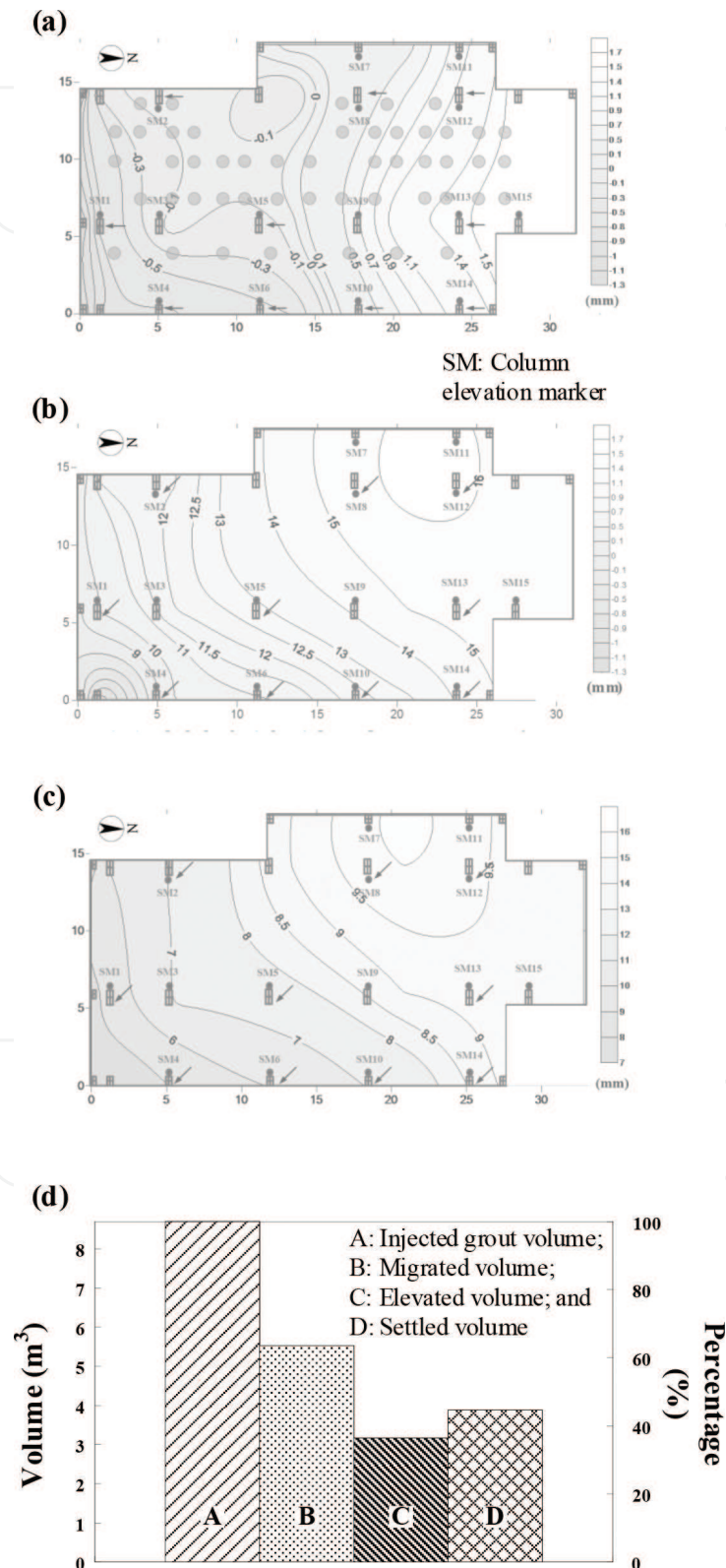


Figure 7. (a) Contour lines of mat foundation before grouting of day one, (b) contour lines after grouting of day one, (c) contour lines before grouting of day two and (d) compensation efficiency from day one (Case B).

Notwithstanding that, the normally consolidated clay owing to the repetitive injection procedure was likely to be changed to the slightly overconsolidated clay. This was verified through the positive compensation efficiency of 4.3% from day four where the elevated, overnight settled and injected grout volumes measured 7.5, 5.2 and 54.7 m³, respectively, as shown in **Figure 8**. The injection was subsequently suspended for 7 days to investigate how long it takes for the excess porewater pressure to dissipate. The results showed that it took 5 days to reach the cumulative settlement of 3.82 m³ being almost identical to the elevated volume of 3.9 m³ at day four, as shown in **Figure 9**. **Figure 10** shows the cumulative elevated, overnight settled, migrated and injected grout volumes, respectively, against each grouting day of this jacking-up grouting. The cumulative elevated volume surpassed the cumulative settled volume at day four, and from day four on, the cumulative elevated volume was greater than the cumulative settled volume for each grouting day. It is due to the fact that the higher the overconsolidated ratio, the lesser the soil compressibility, and the higher the final compensation efficiency. It is inferred that a sand deposit due to its lesser compressibility would provide better compensation efficiency than a clay deposit in general. The final compensation efficiency of 11.1% was derived by subtracting the final settled efficiency of 6.0% from the final elevated efficiency of 17.1%, as shown in **Figure 10**. This eight-storey building originally tilted to the southwest at an angle of 1/190 was restored to near level at an angle of 1/707 in 18 days.

4.2. Lessons learnt

Both the presented grout injection cases adopted two-stage grouting, that is, stabilisation grouting and jacking-up grouting. The results from the Case A showed that from day one on, the elevated volume was greater than the overnight settled volume for each grouting day, leading to the final compensation efficiency being equal to 23.7%. This eight-storey building originally tilted to the southwest at an angle of 1/68 was restored to near level at an angle of 1/328 in 11 days.

Compared to the Case A, the overnight settled volume from day one of this jacking-up grouting for the Case B measured 3.9 m³ was greater than the elevated volume of 3.2 m³, leading to the compensation grouting being equal to -8.2%. The positive compensation grouting of 4.3% was first observed as the cumulative elevated volume of 7.5 m³ from day four surpassed the cumulative overnight settled volume of 5.2 m³. From day four on, the cumulative elevated volume was greater than the cumulative overnight settled volume for each grouting day. The final compensation efficiency measured 11.1% was lower than 23.7% from the Case A, which was most likely due to the inappropriate grout hose system and adopted grout mixture. The use of two-shot grout hose system is not only to minimise the generation of the excess porewater pressure during soil hydrofracturing process but to prevent the negative compensation efficiency from occurring at early stage. Additionally, the shorter the setting time of grout, the lesser the excess porewater pressure generated, and the higher the compensation efficiency. Two-shot grout hose system along with extra quick setting grout may provide an access of achieving a higher final compensation efficiency for lifting of tilted building.

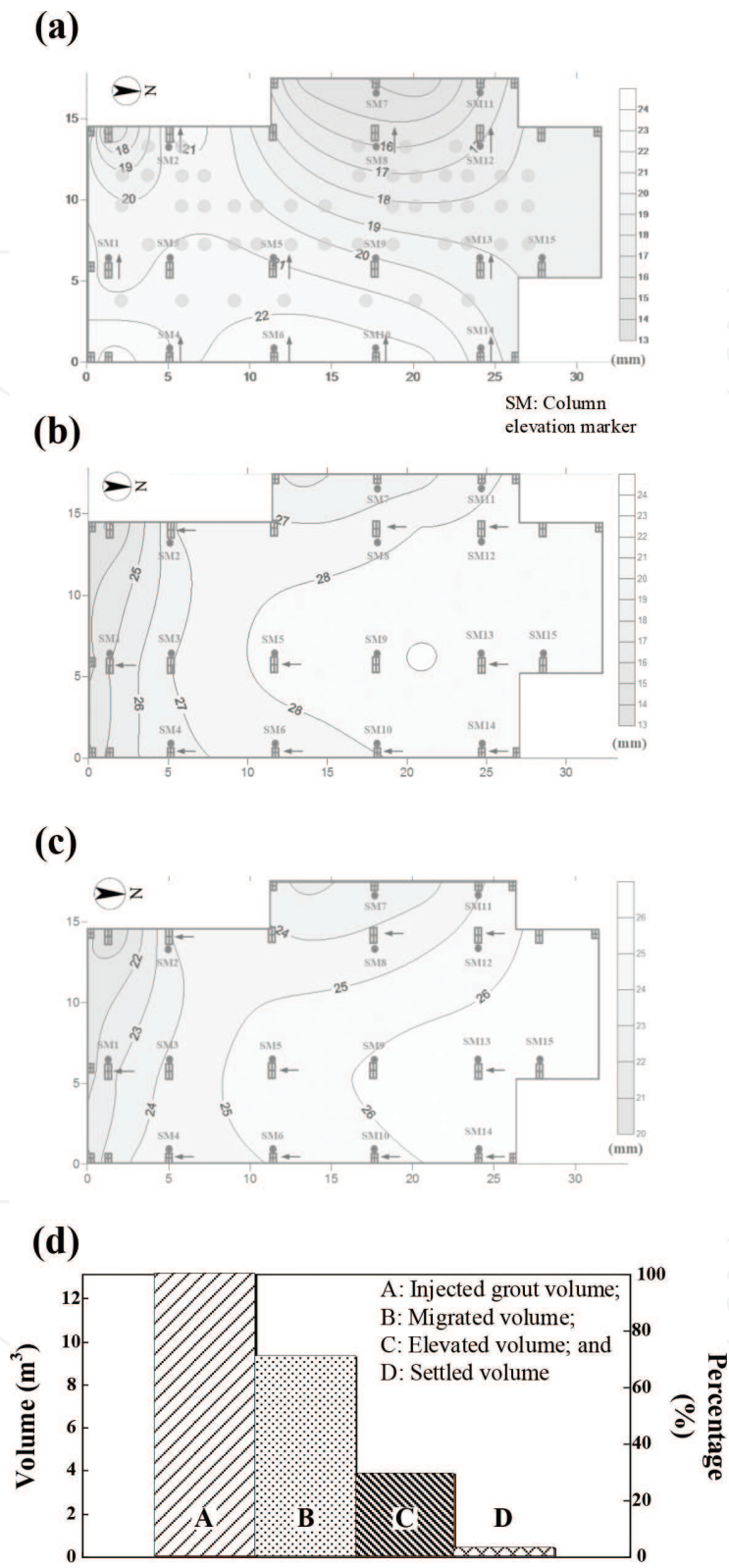


Figure 8. (a) Contour lines of mat foundation before grouting of day four, (b) contour lines after grouting of day four, (c) contour lines before grouting of day five and (d) compensation efficiency from day four (Case B).

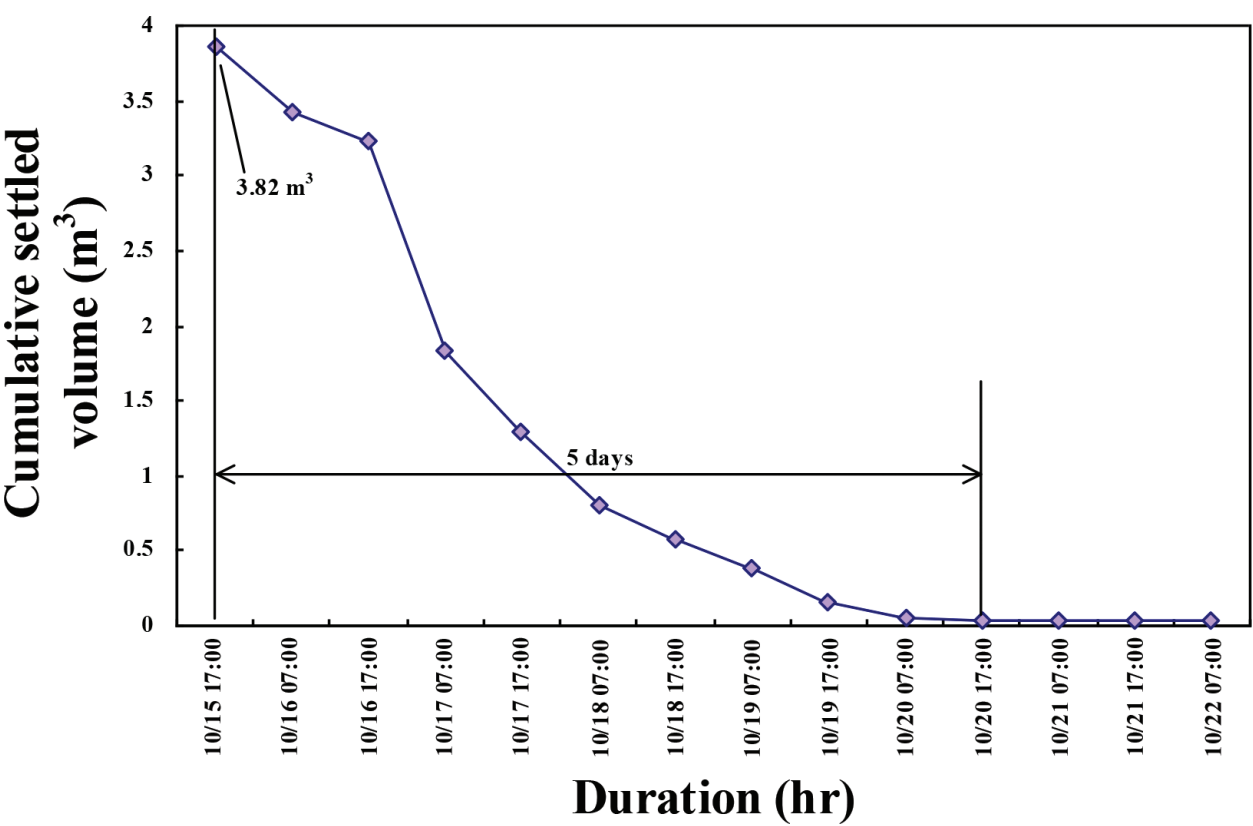


Figure 9. Excess porewater pressure dissipation with time after grouting of day four (Case B).

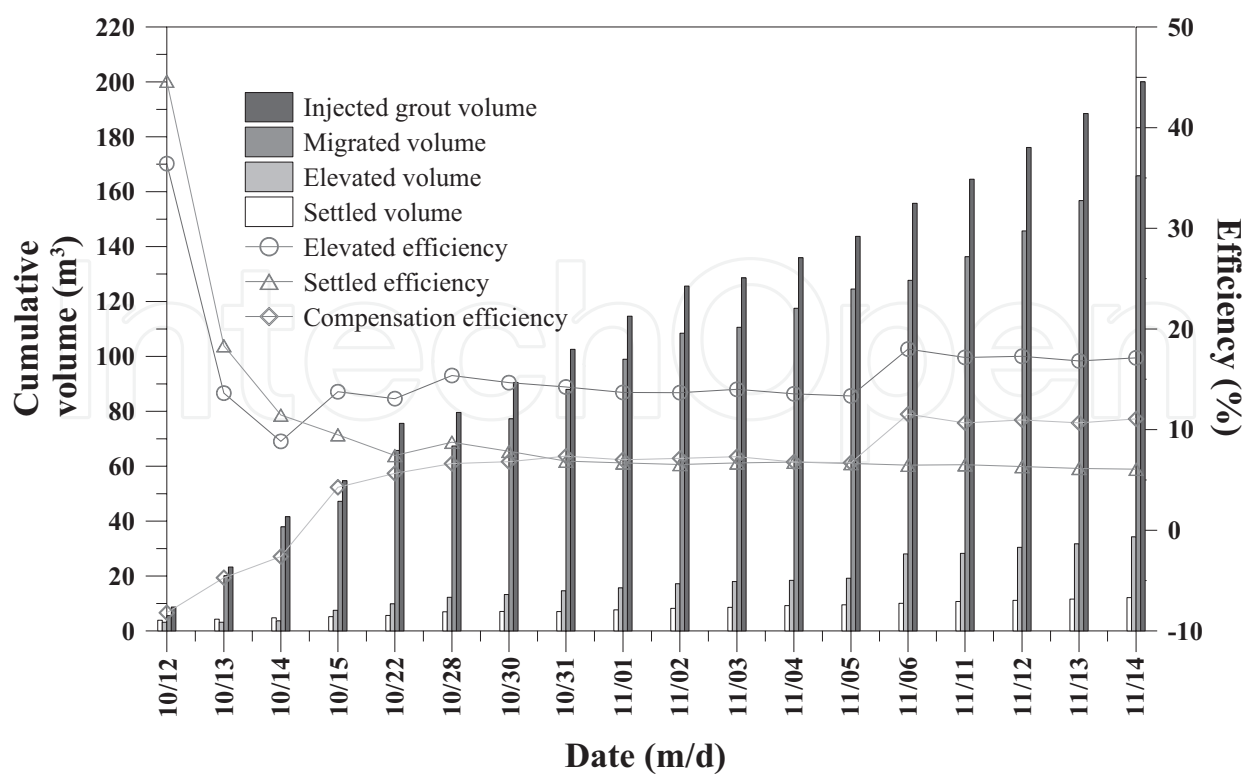


Figure 10. Variations of the elevated, settled and compensation efficiencies for the jacking-up grouting (Case B).

5. Conclusions

From the results of an application of the proposed multiple and simultaneous grouting programme for levelling up the two tilted buildings seated on the soft soil deposits in Taipei basin, the following conclusions can be drawn:

1. Two-stage grouting was deemed to be necessary; the reaction block created from the first stage of grouting (the stabilisation grouting) was to provide the reaction forces required in the second stage of grouting (the jacking-up grouting) to level up the tilted building.
2. Two-shot grout hose system along with extra quick setting grout might be used not only to mitigate the generation of the excess porewater pressure during soil hydrofracturing process but to prevent the negative compensation efficiency from occurring at early stage.
3. The proposed multiple and simultaneous grouting programme gave an effective access of jacking the two tilted buildings back to near level without damaging the structural integrity of their mat foundations.
4. The final compensation efficiency of 11.1% from Case B lower than that from Case A was most likely due to the inappropriate grout hose system and grout mixture. The use of two-shot grout hose system led to a reduced amount of the excess porewater pressure generated during injection, leading to a higher compensation efficiency. The shorter the setting time of grout, the lesser the shrinkage of grout, and the higher the compensation efficiency.

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Conflict of interest

The author declares there is no conflict of interests regarding the publication of this article.

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